FIDO: a Field Integrated Design & Operations Rover for Mars Surface Exploration

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Abstract

We overview our recent development and testing of the FIDO rover, an advanced technology prototype for long range mobile planetary science. The current rover is capable of semi-autonomously navigating to, and gathering multi-modal science data from widely dispersed rock-soil targets of interest. Commands are input to FIDO through a high-level "web" interface enabling geographically distributed and collaborative science planning, sequencing and data analysis. The rover carries a diverse instrument suite: a mast-mounted panoramic science camera, navigational camera, and bore-sighted infrared point spectrometer, also, a front-mounted robot arm with multiple affixed smaller instruments, one being a color micro-imager. FIDO further integrates instrumentation and controls for rock coring. The rover, in form and function, is a model for the NASA Mars Exploration Rovers 2003 mission. We have conducted several recent FIDO trials with mission scientists and flight operations personnel so as to characterize the underlying robotic technologies and science approach. We overview this work, noting highlights of both the rover design and science testing. We comment briefly on related work that extends operations to Mars sample return.

1 Introduction

There is growing international interest in a global exploration of the surface of Mars. Better understanding of Martian surface geology, morphology, geo-chemistry, and atmospheric science will provide important insights to comparative planetary origins, the potential for past-present life, and capabilities of the Mars environment to sustain a long-term human-robotic colonized presence. There are many robotic options for future Mars *in situ* surface science. These include stationary landers, gravitational penetrators, shallow/deep drilling platforms, subsurface "moles", low density airplanes, touch-and-go balloons, and *semi-autonomous* surface mobility. The word "semi" connotes remote planning, command-sequencing and visualization of rover activity sequences and related data products by an earth based science-engineering team—sequences and data return under extreme time delay and intermittent communication afforded by daily uplink/downlink cycles of deep space networks.

Figure 1: FIDO Rover during its 1999 field testing activities on a cobbled bed, Silver Lake, California, with mast/instrument arms extended. Inset depicts the continuous traverse of a nearby sand wash, rover seen in rear view, mast/instrument arms now stowed.

Related robotics developments by our JPL group include a "MarsArm" lander-manipulator prototype [1] that became basis for NASA's 1998 Mars Polar Lander. More recently, we have focused on mobile science and sample return, exploring various mobility design and operational concepts across a range of small to medium scale vehicles [2]. The most mature of these is FIDO rover, **Figure 1**, above.

NASA near-term program plans for Mars surface exploration emphasize longer ranging mobility and *in-situ* science. Such vehicles, operating over-the-horizon and free of lander constraints, will enable new kinds of remote planetary field geology. For example, the upcoming NASA Mars'03 mission (Mars Exploration Rovers) should greatly extend the physical and observational scope of an earlier 1997 NASA Mars Pathfinder/Sojourner flight experiment [3]—from 10's of meters about a nearby lander, upon which the rover depended for both area imaging and communications (carrying arear-mounted instrument, the AXPS/Alpha X-ray Photon Spectrometer)—to 1000's of meters over variable terrain, using twin rovers capable of wide area imaging and direct-to-earth communications (carrying a mast-mounted high resolution multi-spectral panoramic camera, near-IR spectrometer, thermal emission spectroscope, also, arm-mounted instruments such as a color micro-imager, Mössbauer spectrometer, and rock abrasion tool).

In the sections ahead we provide several different perspectives on FIDO rover, field trial applications and directions of related development. Section 2 outlines the FIDO concept, general architecture, operational approach and deployment into past field testing activities. Section 3 treats the FIDO architecture in more detail, overviewing the software and functional organization of the vehicle. Section 4 comments on some paths of forward JPL technology development related to FIDO. Finally, in Section 5 we conclude, and note our latest field testing plans.

2 FIDO Rover Concept and Testing

As noted above, FIDO is a technology integration and mission simulation testbed for semi-autonomous *in situ* science exploration. The usual operational paradigm for this class of rover is as follows: Based on down-linked panoramic imagery, as obtained from a rover-mounted camera/s, scientists designate nearby target(s) of interest to which the rover navigates via intermediate way-points. These are designed ground coordinate locations, as referenced to the rover world frame and/or features autonomously recognizable by on-board sensing (information which taken together constitute part of trajectory sequence planning). The rover visually detects and avoids local obstacles en route, while updating absolute trajectory coordinates. Rover localization over short distances is projectable from on-board odometry and inertial measurements; extended traverses is referenced to sun-sensor absolute heading. Either source can be supplemented by visual terrain tracking/matching. In any case, it is usual and safe practice to confirm a hypothesized rover position by ground analysis—contrasting latest rover down-link imagery with an expected position (re-initializing local position in a larger panorama, setting as needed new local coordinate frame references for science activities). In the case of FIDO, remote command and control is implemented via ***WITS*** (Web Interface for TeleScience), a JPL-developed toolset for cooperative, geographically distributed robotic science operations [4], WITS, **Figure 2,** has diverse resources for science planning, 3D pre-and-post-visualization of sequences, uplink command-telemetry, science-engineering data product downlink/ display and more.

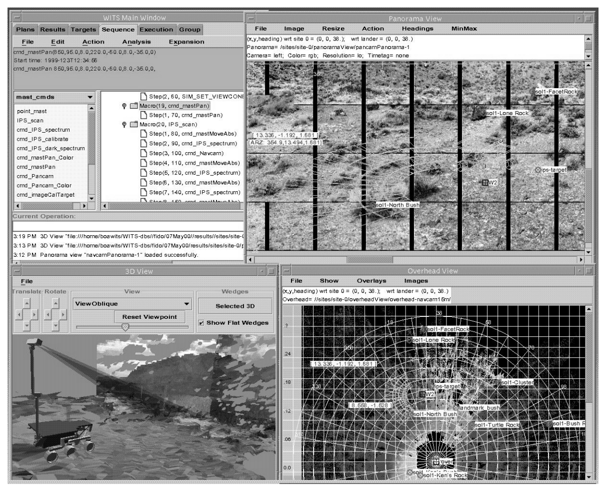


Figure 2: A Web Interface for Telescience (WITS) display as is seen by a single operator at a PC/Unix-based workstation (operators at different sites can simultaneously exercise different features/displays).

Table 1, next page, summarizes the key FIDO design features. These include wide-area panoramic imaging (mast-mounted color stereo pair), 3D terrain mapping and hazard avoidance (B/W stereo navigation camera on mast; chassis-mounted front/rear stereo), visual self-localization (visual registration/tracking of natural and artifactual features), local path planning (with respect to derived stereo/navcam maps), inertial and celestial navigational references (e.g., accelerometers, gyro, CCD sun sensor [5]), and finally—in reference to the above rover localization issues—fused state estimation for long range navigational guidance (viz., statistical integration of odometry, visual, inertial, sun sensor and other data sources via Extended Kalman Filtering and related techniques, per [6]).

Mobility & Manipulation

- 6-wheel rocker-bogie, all wheels independently driven / steered
- max speed 9 cm/sec, 20 cm wheels, ground clearance 23 cm
- multiple mobility modes (turn-in place, "crab", passive/active wheel drive); max obstacle clearance ~1.5 wheel diameters
- rover dimensions, 1.0m (L) x 0.8m (W) x 0.5m (H); 68 kg mass
- 4 d.o.f. articulated mast with integral science instrumentation
- 4 d.o.f. fully actuated and instrumented front science arm

Navigation and Control

- PC104+, 266 MHz Intel Pentium, PCI/ISA bus, 64 MB RAM
- ANSI C software architecture under VxWorks 5.3 real-time OS
- front/rear hazard avoidance stereo camera pairs (115° H-FOV)
- mast-mounted navigation stereo camera pair (43° H-FOV)
- inertial measurement unit (IMU) and CCD-based sun sensor
- differential GPS for ground-truth reference of traverse

Science Instrumentation

- mast-mounted multi-spectral stereo camera pair (650, 740, 855 nm, 10° FOV, .34 mrad IFOV); full extent is 1.94 m
- mast-mounted near-infrared point spectrometer (1.3-2.5 microns, 9.3 mrad projective field of view)
- arm-mounted color micro-imager (RGB color, 512x496 pixel, 1.5x1.5cm2 FOV at approx. 3 mm standoff), and Mössbauer spectrometer; arm reach is ~50+ cm)
- rover-mounted Mini-Corer with belly stereo camera

Table 1: FIDO system features; for more detailed information on the various rover subsystems, see the JPL FIDO public web site http://fido.jpl.nasa.gov

We are characterizing FIDO rover—its underlying sensing, control, manipulation, sampling technologies and related remote science operational strategies—in an increasingly challenging set of science field trials under direction of NASA's MER'03 flight science team (PI Steven Squyres, Cornell University, co-I Raymond Arvidson, Washington University). A first trial at Silver Lake, California, in the Mojave desert, per **Figure 1**, demonstrated a "local sampling loop" about a putative lander site: panoramic imaging from the lander area, 3D navigational mapping to ground-designated targets of interest, open-loop traverses to selected targets, bore-sighted IPS imaging of targets in stand-off scanning and proximity pointing modes, kinematics-referenced 3D visualization and placement of mast/arm mounted instruments & tools, targeting and extraction of rock samples, and finally, return to the immediate area of the lander. A sequel field trial in spring 2000 at Black Rock Summit, Nevada, added significant new elements of Mars mission realism and complexity. In particular, operations were "blind" and fully remote. That is, the science team controlled FIDO rover by satellite communications from JPL and their prior knowledge of the site was limited to large area thematic and descent imagery typical of real Mars orbital observations.

The first action of the FIDO *Science Operations Working Group* (SOWG) stationed at JPL was to acquire a full panorama looking out ~ 50-100 meters and correlate this extensive visual data set with multi-source overhead thematic visible and infrared imagery (including LANDSAT7+, TIMS, calibrated AVIRIS, typically at 10-to-30 meters^2 per pixel resolution; the available data sets also included un-calibrated aerial photographs, oblique perspective views, et al.). Once so "situated", the SOWG performed a prospective analysis of nearby targets of opportunity, ranking their science values against hypotheses about geological and mineralogical structure. Some targets were close enough to allow an immediate near-IR analysis via pointing of the mast-mounted IPS. This work done, the SOWG picked primary targets and commanded rover approaches. The terrain, as illustrated below, was quite challenging and rich. This motivated a very opportunistic, incremental exploration in which the investigators frequently stopped the rover, deploying its arm-mounted micro-imager to examine ground soils and rocks en route to a primary target. A sense of the over-all activity is depicted in **Figure 3,** with FIDO rover having already acquired and down-linked a panorama, and now beginning its local science in a near field of the 1:1 scale lander mock-up.

Figure 3: *FIDO Rover* at the Nevada blind field test, egress from lander complete, and beginning its science mission. Pictures at upper and lower right: composite LANDSAT data and LANDSAT overlay of 3D TIMS reconstruction. See also http://wufs.wustl.edu/fido

In the aggregate, simulated Mars *in situ* mobile science of the 2000 field trial was akin to terrestrial field geology [7]—a somewhat non-linear process of scientific discovery-and-discernment wherein multiple hypotheses were incrementally formed based on initial data and area history, then progressively updated, refuted, confirmed or dismissed (at times the overall investigation being redirected as a new observation of yet highest perceived priority was made). The SOWG, science investigators, engineering, and operations staff learned a great deal from this multi-week experiment. Some of the insights gained were: 1) preferred science operational strategies and command-data sequencing protocols under fairly realistic time and bandwidth constraints; 2) limitations and impacts of open loop localization of rover and instrument arm placement in a locale during target acquisition (processes involving coordination of rover motion with inverse kinematics positioning of arm-mounted instruments, also, the rover-mounted mini-corer, relative to 3D stereo maps taken from hazcam-bellycam-navcam); and finally, 3) need of continuing development for 3D visualization (supporting rover activity planning and instrument operations), resource models for sequence planning (time, power, data volume, etc.), command-dictionary structure, downlink telemetry processing, automated report generation & data archiving, and overall task simulation, within WITS and related tools.

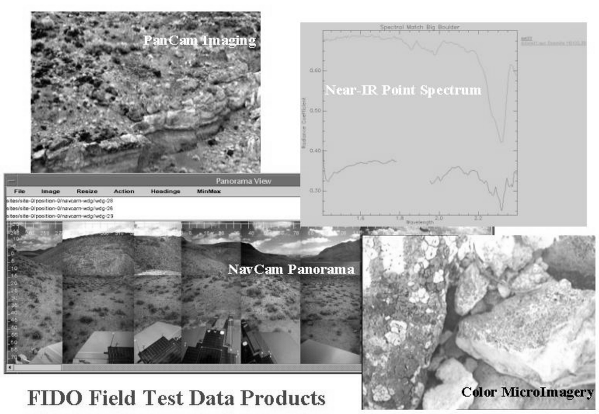


Figure 4: Representative data products from FIDO Rover field test at the Nevada. (Upper left), near-field Panoramic Camera sector; (lower left, Navigational Camera mosaic; (upper right), Infrared Point Spectrometer analysis of target; lower right, close-up of ground rock structure taken with micro-imager. See also http://wufs.wustl.edu/fido

In summary, robotic science experiments at this level of integration and scale yield not only significant insights to component technology capabilities and operational limitations, but also give serendipitous findings about operational strategies, e.g., interactive staging of the rover PanCam, IPS and micro-imager observations during driving; trends in resource utilization; and; the most useful roles and relative merits of visualization and simulation tools.

3 FIDO Architecture

This section overviews key features of FIDO design approach—not just the current rover per se—rather, the overall concept of FIDO as functional architecture and tools for the development of mobility platforms. At large, *Field Integrated Design & Operations is a set of common module design resources*, based in:

- mechanical hardware
- electronics and computing hardware
- sensors and actuators
- real-time on-board software
- mission operations software and tools

We have used these resources to rapidly prototype very different robotic systems, testing the resulting designs, embedded functions, operational concepts in various mission scenarios. The "FIDO rover" itself is the most mature of these systems; in summary, FIDO is a development environment and underlying mobility system architecture for end-to-end operations.

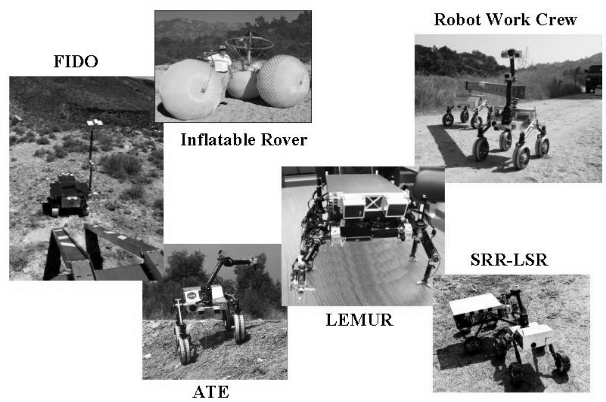
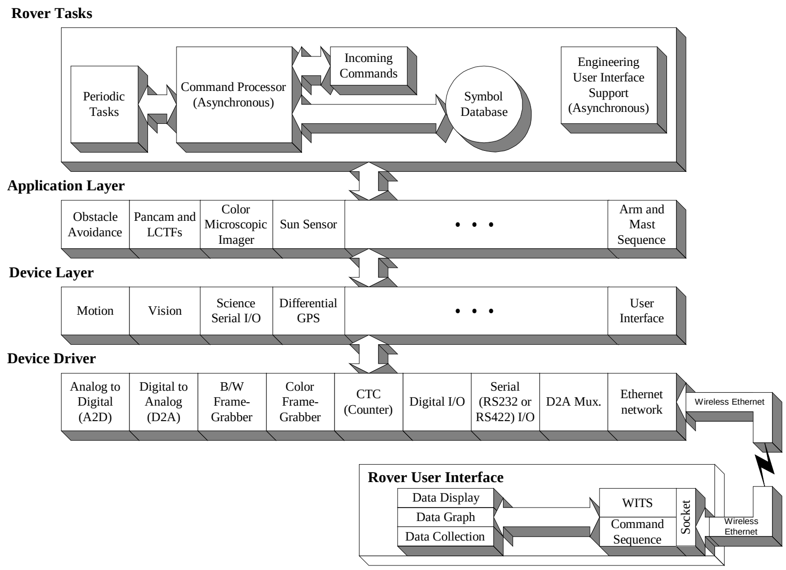


Figure 5: "FIDO family" to date, starting from left—FIDO rover; long-ranging, inflatable rover; multiple rovers that can tightly coordinate their kinematic and force constraints in "work crew"-like tasks; small and highly autonomous Sample Return Rover for visually guided field rendezvous and sample cache retrieval; a kinematically reconfigurable rover that can adaptively traverse extremely rugged terrain; and a legged robot with modular tool change-out for possible platform inspection maintenance and servicing [2].

FIDO's efficiency as a mobility system design-and-implementation environment is strongly rooted in its software architectural approach. We sought an extensible and open design that would easily flow in new functional codes—also, in turn, enable its end users to extract successful products as very simple, compact, and generalized ANSI "C" routines.



Operating System

- VxWorks 5.3 (Tornado)
- Turnkey bootable from solid state disk

Three Tier Architecture

- Device drivers (to hardware interfaces)
- Device layer (abstracted to generalized i/fs)
- Application layer (navigation/telemetry/etc.)

Software

- All code written in “clean” ANSI C
- Object oriented, modular, portable, small
- Supports multi-threaded tasking

Timing/Control Rates

- Hard periodic tasks run at 200 Hz, including
  - A/D conversion, encoder data collection
- Additional processes run off these tasks
  - Actuator motion control (50 Hz)
  - IMU data collection/processing (50 Hz)
  - Motion control synchronization (10 Hz)
  - Health monitoring (10 Hz)

Figure 6: Organization of FIDO Software Architecture and Some of its Key Features

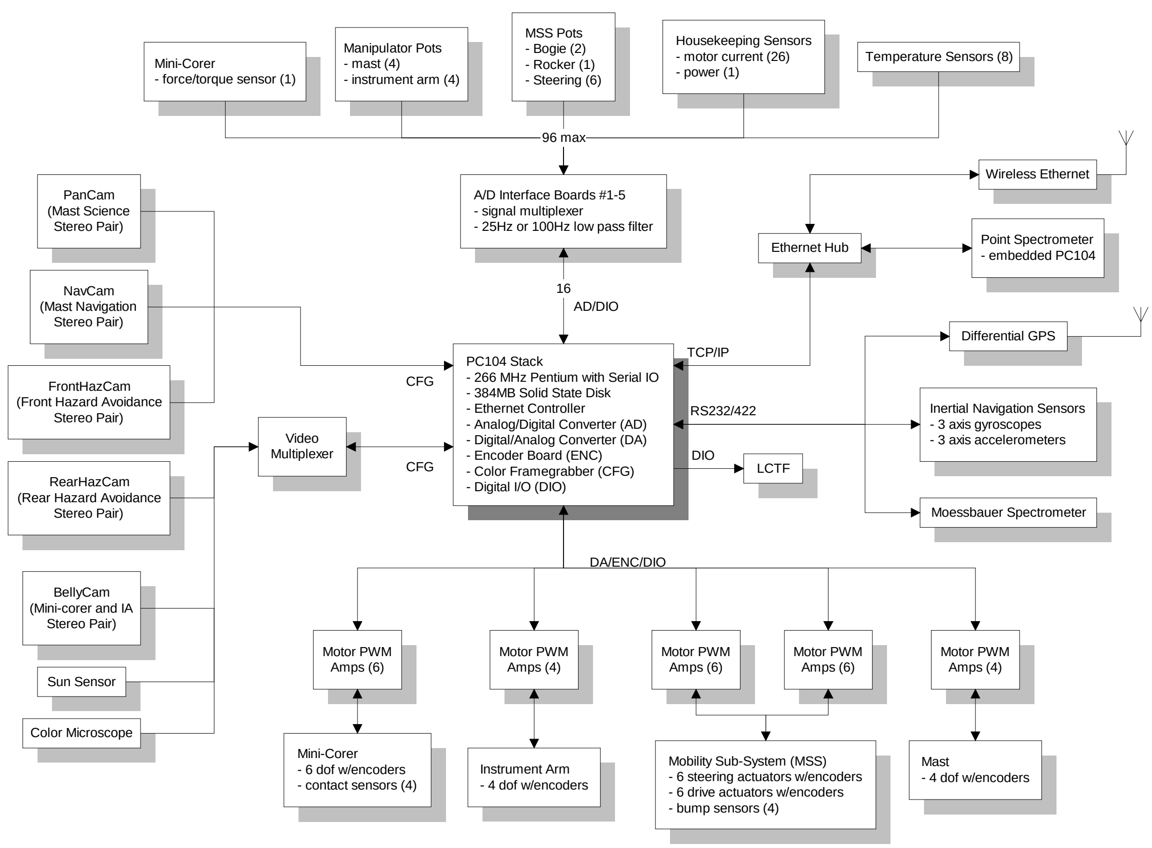


Figure 7: Functional Block Diagram of the FIDO Rover Showing its Key Computing/Electronics Interfaces

As indicated in **Figure 6**, the FIDO on-board real-time computing environment is self-supporting, with strong partitioning of specific hardware features/interfaces from sensor-motor functions via a generalized driver layer. This construct greatly enhances fieldability, and makes the integration of new sensing, control, and other code modules very transparent. Recompilation of code is straightforward, and indeed, we have readily performed in-field modifications using simple laptop development and debug tools. Overall we from the outset conceived FIDO architecture in the spirit of current design practice in modular, hard real-time aerospace systems: The real-time kernel is small; the executables are fast; the underlying code objects are small and general; the code structure is very general and open, carrying a minimum overhead in memory or OS support on re-integration; the development tools that support FIDO coding are widely available and understood, many of them being in the freeware domain. Thus, the FIDO environment as a whole is exceptionally attractive to migrate across new mobility platforms, and has become a significant R&D rapid prototyping resource in JPL's Planetary Robotics Lab that is cognizant for FIDO development.

4 Continuing Technology Development

There are many potentially important directions for future Mars surface mobility development. Among those of current interest to NASA are achieving higher levels of on-board autonomy and capability for a Mars sample return. We have for the last few years pursued each of these through more basic research tasks, as have our NASA/JPL colleagues. We are progressively infusing some of the resulting concepts into the FIDO rover for field evaluation, and briefly overview those developments here. There are of course other lines of promising mobility development for Mars application; examples include robotic mechanization and control regimes enabling access and safe traversal of much more challenging terrain (so called "high risk access") as well as cooperative multi-robot systems for future Mars outposts or science network deployment. See our related paper of this meeting for a brief overview of some examples of such "All Terrain Rovers" and "Robot Work Crews" [8].

We briefly discuss two recent lines of development that we expect to be of importance in near-to-mid term Mars surface missions. The first is autonomous rover rendezvous for sample return; the second is automated rover localization and science arm deployment.

4.1 Rover Rendezvous & Mars Sample Return

Figure 8 illustrates our recent development of a lander based sample return operation. The mission concept that motivates this work is the idea of a science rover making repetitive "loops" into the field, periodically returning to a lander ascent vehicle, and depositing its latest acquired sample cache contents in a protective containment. The samples themselves are typically rock cores and nearby soil substrates; FIDO carries a related "mini-corer" that has been demonstrated in the field under visually guided positioning.

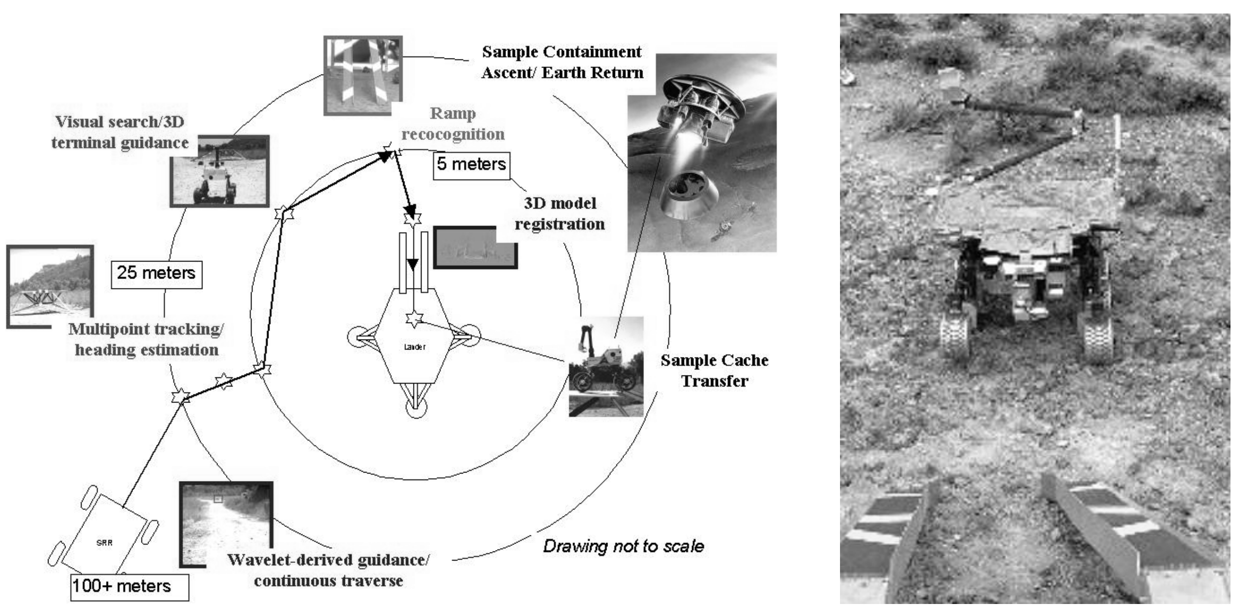


Figure 8: (Left) Operational scenario for rover rendezvous with Mars lander/ascent vehicle (the pictures within show our Sample Return Rover research prototype; (Right) as implemented on FIDO, final approach in progress

The objective, then, is to quickly rendezvous the returning science rover with a lander-based Mars ascent vehicle (MAV) complex. There are two underlying issues. First, the rover must determine location of the lander, then approach and physically engage it from considerable distances. Second, such operations must not be ground-intensive, requiring multiple uplink/downlink cycles per "loop"; rather, primary mission time must go to science. Thus, there is need to develop and demonstrate techniques for autonomous and accurate terminal rendezvous of the rover with artifactual structures. We note in passing that there are corollary mission scenarios, "on-board mini-MAV" and "in-field rendezvous". In the first case, the rendezvous problem is finessed by having a small MAV as part of the rover platform itself (This of course has its own implications to rover size, sample transfer mechanization, etc). The second case has variants and is in the general theme of using a small, fast sample return rover interact with field repositories and science platforms—divide and conquer. We have explored this mission architecture in some technical detail as regards the rover rendezvous problem [9] and summarize our key results in **Figure 9**.

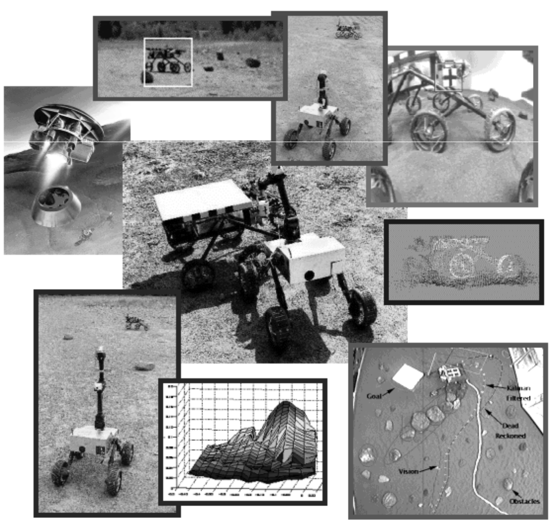


Figure 9: Starting from lower left, the SRR (cache retrieval rover) in near-field approach to LSR (science rover) and mid-field obstacle avoidance; Mars ascent vehicle depiction; wavelet-based image localization of LSR from SRR goal camera; terminal goal-camera guidance and staging for normal vector approach; eigenvector-based recognition/localization of cache; 3D feature set of LSR used in final approach 3D registration/localization; rover experiment on fused visual tracking/odometry navigation; and bottom center, derived 3D map for hazard avoidance. In the middle, visually referenced sample cache pick-up.

The direct-to-lander rendezvous approach by a single rover is the now-assumed concept for sample return for small rover missions. Where it is feasible to fly a large entry payload, landing a significant fraction as mobile mass, then on-board MAV would seemingly be preferred. We have used, per Figure 7 earlier, FIDO as a testbed for lander-rover rendezvous studies, in one case conducting such work as part of the FY00 field trial. This development, which was initiated in our Sample Return Rover task, and migrated into the FIDO vehicle, provides these new capilities:

- autonomously detecting a Mars '03 replica lander structure from over 125 meters via wavelet-based techniques (similar to those used in Figure 8)
- tracking to a mid-range of 20-to-60 meters, then visually acquiring a more detailed multi-point geometric map of lander locations of interest
- approaching the lander closely (several meters), then developing a very accurate and robust fused feature map of lander structure, using same to move into closure of a meter or less, and finally
- registering (localizing) FIDO to within 1-3 cm and 1-2 degrees accuracy at the lander ramp entry point.

This is all done under sequentially staged autonomy, starting from fairly arbitrary approach directions.

4. 2 Rover Localization and Enhanced Autonomy

We noted earlier the important role that accurate rover localization plays in science planning and operational safety. Equally important, good localization in concert with visually servoed manipulation can enable very high productivity science—ideally leading to a "go-to" sampling capability wherein science investigators can designate targets of opportunity in a panorama and in a single uplink/command cycle, access a new target. To this end, we and colleagues have developed and begun to evaluate on FIDO rover various techniques for improved autonomous rover localization, also visual closed-loop arm-instrument deployments. This includes visual terrain tracking and surface matching to estimate rover motion [10], fused estimation of same based on integration of multiple data sources [6], and local spatial planning. The last, the "rover-bug" algorithm, uses an extended stereo navigational vision map to reactively plan imaging operations, choosing incremental optimal views and searching for a clear path to specified goal. The underlying algorithm and search uses a convex hull representation of sensed obstacles and C-space path planning, requiring mast deployment every 5-10 meters and assuming accurate traversal between planning steps [11].

5 Conclusion and Future Directions

As this paper is written the FIDO rover is at a "blind" desert site, under remote operations from JPL. The purpose of this latest yearly field trial is NASA MER/ Mars'03 simulation of 20 sols of the baseline mission plan. The mission science team, operations personnel and FIDO team are performing the simulation under realistic constraints and command sequencing models for time-line, power, data downlink and contingency handling. In fall 2001, FIDO will proceed to a yearly demonstration/evaluation wherein newly integrated technology functions will be tested in realistic mission sequences—automatic approach to targets, auto-focus of the end-arm color micro-imager, instrument arm collision detection/management, and other.

Figure 10: FIDO rover FY 2001 field trial in progress under command from the JPL Planetary Robotics Lab.

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References

[1] P. S. Schenker, D. L. Blaney, D. K. Brown, Y. Bar-Cohen, S-S. Lih, R. A. Lindemann, E. D. Paljug, J. T. Slostad, G. K. Tharp, C. E. Tucker, C. J. Voorhees, and C. Weisbin, Jet Propulsion Lab.; E. T. Baumgartner, Mich. Tech. Univ.; R. B. Singer, R. Reid, Univ. of Arizona, "Mars lander robotics and machine vision capabilities for *in situ* planetary science," Proc. SPIE Vol. 2588, Intelligent Robots and Computer Vision XIV, Philadelphia, PA, October, 1995; and, P. S. Schenker, E. T. Baumgartner, S. Lee, H. Aghazarian, M. S. Garrett, R. A. Lindemann, D. K. Brown, Y. Bar-Cohen, S. S. Lih, B. Joffe, and S. S. Kim, Jet Propulsion Laboratory; B. H. Hoffman, Massachusetts Institute of Technology; T. L. Huntsberger, Univ. of So. Carolina, "Dexterous robotic sampling for Mars in-situ science," Intelligent Robotics and Computer Vision XVI, Proc. SPIE Vol. 3208, Pittsburgh, PA, Oct. 14-17, 1997.

[2] P. S. Schenker, T. L. Huntsberger, P. Pirjanian, and E. T. Baumgartner, "Planetary rover developments supporting Mars science, sample return and future human-robotic colonization," to appear in Proc. 10th Intl. Conference on Advanced Robotics, Budapest, Hungary, Aug 22-25, 2001 (invited).

[3] The Rover Team [D. L. Shirley at al.], "The Pathfinder Microrover," Jrnl. Geophysical Research, Vol. 102, No. E2, pp. 3989-4001, Feb. 25, 1997; D. L. Shirley and J. R. Matijevic, "Mars rovers: past, present, and future," Proc. Princeton Space Studies Inst. 20th Anniversary Conf., May, 1997.

[4] P. G. Backes, K. S. Tso, and G. K. Tharp, "The Web Interface for Telescience," Presence, Vol. 8, No. 5, pp. 531-539, Oct. 1999; P. G. Backes, J. S. Norris, K. S. Tso, G. K. Tharp, and P. C. Leger; "Sequence planning for the FIDO Mars rover proto-type, submitted to Jrnl. Geophysical Research—Planets.

[5] A. Trebi-Ollennu, T. Huntsberger, Y. Cheng, E. T. Baumgartner, B. Kennedy and P. Schenker, "Design and analysis of a sun sensor for planetary rover absolute heading detection," submitted to IEEE Trans. Robotics and Autom.

[6] B. D. Hoffman, E. T. Baumgartner, T. Huntsberger, and P. S. Schenker, "Improved rover state estimation in challenging terrain," Autonomous Robots, Vol. 6, No. 2, pp. 113-130, 1999, and references therein; also, E. T. Baumgartner, H. Aghazarian, A. Trebi-Ollennu, T. L. Huntsberger, and M. S. Garrett, "State estimation and vehicle localization for the FIDO Rover," Proc. SPIE Vol. 4196, Sensor Fusion and Decentralized Control in Robotic Systems III, Boston, MA, Nov. 5-8, 2000.

[7] R. E. Arvidson, S. Squyres, E. T. Baumgartner, L. Dorsky, and P. Schenker, "Rover trials for Mars Sample Return mission prove successful," EOS Transactions, American Geophysical, Union, Vol. 81, No. 7, pp. 65-72, Feb. 2000; and R. E. Arvidson, C. Niebur, K. Larsen, F. Seelos, N. Snider, B. Jolliff , Washington Univ.; S. W. Squyres, Cornell Univ.; E. Baumgartner, P. Schenker, Jet Propulsion Lab.; "FIDO prototype Mars rover field trials, Black Rock Summit, Nevada, as test of the ability of robotic mobility systems to conduct field science," submitted to Jrnl. Geophysical Research – Planets.

[8] P. S. Schenker, T. L. Huntsberger, P. Pirjanian, Jet Propulsion Lab.; G. T. McKee, Univ. of Reading; "Robotic autonomy for space: cooperative and reconfigurable mobile surface systems," Proc. 6th Intl. Symp. on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS'01), Montreal, Canada, June 18-21, 2001.

[9] P. S. Schenker, E. T. Baumgartner, R. A. Lindemann, H. Aghazarian, D. Q. Zhu, A. J. Ganino, L. F. Sword, M. S. Garrett, B. A. Kennedy, G. S. Hickey, A. S. Lai, and L. H. Matthies; Jet Propulsion Lab.; B. D. Hoffman, Massachusetts Inst. Technology; T. L. Huntsberger, Univ. So. Carolina, "New planetary rovers for long range Mars science and sample return," Proc. SPIE Vol. 3522, Intelligent Robotics and Computer Vision XVII, Boston, MA, Nov. 1-5, 1998; also, T. L. Huntsberger, E. T. Baumgartner, H. Aghazarian, Y. Cheng, P. S. Schenker, P. C. Leger, K. D. Iagnemma, and S. Dubowsky, "Sensor-fused autonomous guidance of a mobile robot and applications to Mars sample return operations," Proc. SPIE Vol. 3839, Sensor Fusion and Decentralized Control in Robotic Systems II, Boston, MA, Sep. 19-22, 1999.

[10] C. Olson, "Probabilistic self-localization for mobile robots, IEEE Trans. on Robotics & Autom., 16(1): 55-66, Feb 2000.

[11] S. Laubach and J. Burdick, "An autonomous sensor-based path-planner for planetary microrovers," IEEE Conference on Robotics and Automation, Detroit MI, May 1999.